# Modeling and Analysis of Diffuser Augmented Wind Turbine

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***Abstract*- Renewable energy resources are becoming an increasingly important part of our total energy demands due to the depletion of fossil fuels and the emergence of global warming. Wind turbines are one type of renewable resource that is very usual in the South Texas region. It is a fact that wind power is the best dilute and unpredictable source of energy that works with efficiency of great importance in the conversion of this energy to electricity. Our research was to add shrouds by means of computer simulations to encase the "bare turbine" thereby increasing efficiency. Our goal was to find a particular shroud that maximized air mass flow through the turbine beyond the best bare turbine operational conditions.**

***Keywords- Wind Turbines; Wind Power Efficiency; Wind Turbines Shrouds; Renewable Energy; Windmills***

## I. INTRODUCTION

The ideal, frictionless efficiency of a propeller (horizontal axis wind turbine, HAWT) was predicted by Betz in 1920. The propeller is represented by an actuator disk, which creates across the propeller plane a pressure discontinuity. The wind is represented by a stream tube of approach velocity $V_1$ and a slower downstream wake velocity $V_2$ (Fig. 1). The pressure rises to $P_b$ just before the disk returning to free stream pressure in the far wake and drops to $P_a$ just after. A force F is needed to offset the wind pressure on the propeller [3].

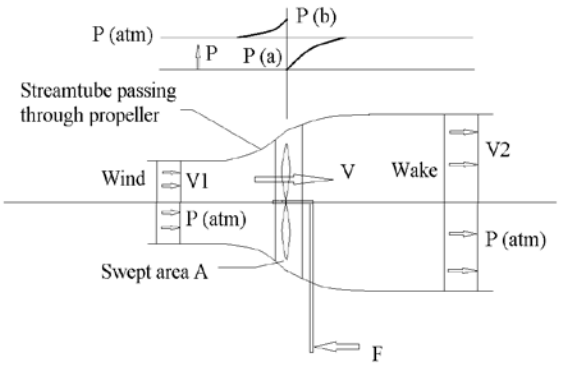



Fig. 1 Betz stream tube analysis of power extraction from a windmill [3]

The maximum available power to the propeller is the mass flow through the propeller times the total kinetic energy of the wind [3]:

$$\text{POWER available} = \tfrac{1}{2}\,\dot{m}\,(V_1)^2$$

$$= \tfrac{1}{2}\,\rho A (V_1)^3 \qquad (1)$$

Where $\dot{m}$ = mass flow rate, $\rho$ = air density, and A = swept area of blades.

From the work of Betz, the maximum possible efficiency of an ideal frictionless wind turbine is usually stated in terms of the power coefficient Cp:

$$Cp = \text{POWER} / \tfrac{1}{2}\,\rho A\,(V_1)^3 \qquad (2)$$

$$Cp_{max} = 0.593. \qquad (3)$$

As stated in the abstract, efficiency is of great importance for the generation of electricity from wind power since the wind is a dilute source of energy [1]. It is a common practice to place wind turbines on ridges and hills to increase wind velocity over that of free stream. If a device (shroud) can be added to a bare turbine to increase wind velocity just as the topography as mentioned above, then efficiency can be increased. Since power available in the wind is proportionate to the cube of wind velocity, small gains in wind velocity can mean large gains in shaft power. The diffuser shroud is one such device to increase wind velocity over that of free stream [1].

A diffuser (conic section) increases the velocity of the airflow (wind velocity) through it. This increase is due to the effect of a region of sub-atmospheric pressure downstream of the diffuser [1], a condition unlike that of a ducted diffuser (i.e. airflow on inside only, with the goal of increasing pressure downstream). Nozzles likewise increase the velocity kinetic energy of a fluid. This is accomplished with a concurrent decrease in pressure, and a favorable gradient, which discourages wall separation of the fluid. The Bernoulli equation gives more favorable result due to this fact [3].

However, in our case, we have fluid flow through and around the nozzle. In this paper, we propose to model and analyze, by means of computer simulations, horizontal axis wind turbines (HAWT) with propeller type blades with the addition of various nozzle and diffuser shrouds encasing the bare turbine to increase shaft power for a given wind velocity of 20 m/s and a given turbine angular velocity of 60 rpm. As mentioned, the diffuser is a conic section that increases wind velocity above that of the free stream velocity. With the nozzle shroud configuration, this is not the case.

In fact, the free stream wind velocity is somewhat diminished, as will be shown later in this paper. We will also investigate a special "Stream tube" shaped shroud. Lastly, we will investigate the effect of turbine rpm for a given shroud and a given free stream wind velocity of 20 m/s on shaft power. Therefore, we shall focus on the diffuser/nozzle design encasing the turbine rather than on the turbine design itself (the turbine design is not changed in our simulations).

## II. MODELING

Our model starts with a simple 3-bladed turbine with a hub simulating the enclosure for the bearings, generator windings, etc. The outer diameter of the blades is four feet (Fig. 2).

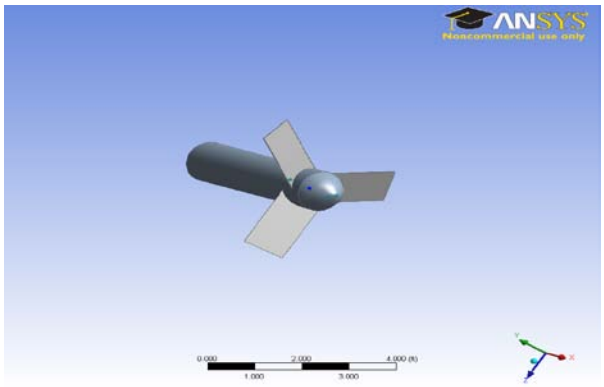



Fig. 2 Bare turbine without shroud

Our shrouds (except "Stream tube") consist of a cylindrical section four feet long attached to a conic section also four feet long. The inside diameter of the shroud is slightly larger than the turbine and the turbine is placed at the midpoint of the shroud. The conic section comprises the nozzle or diffuser portion of the shroud (Fig. 3).

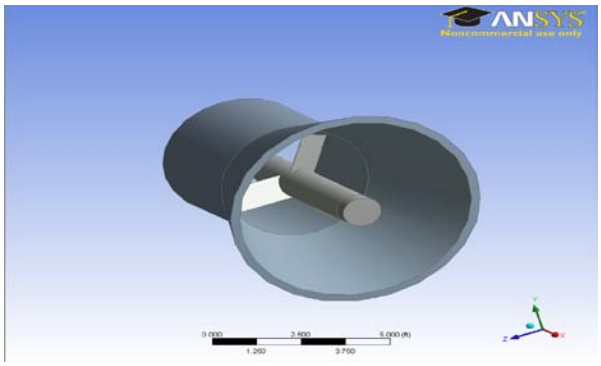



Fig. 3 Turbine assembly inside diffuser shroud

We shall use the computational fluid dynamics program "CFX" which is a part of the ANSYS 12.0 software package, to create the geometry of the HAWT and diffuser/nozzle, and to do the computations and display the results, as we change parameters of the diffuser/nozzle. The CFX program uses a finite element analysis to solve applicable differential equations of fluid flow through and around solids.

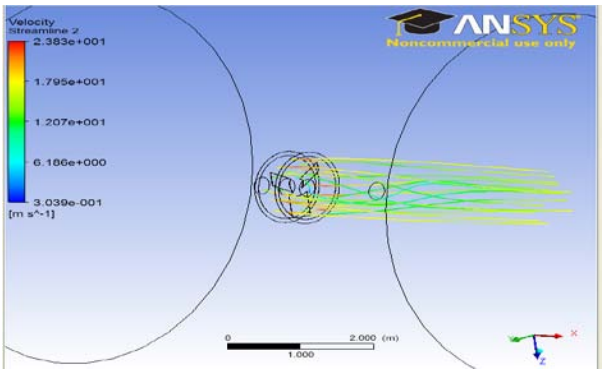



Fig. 4 Simulation of bare turbine

We first investigate the shaft power of our bare turbine in a free wind stream as a baseline for our data. We choose to investigate small residential turbines, because adding a diffuser to a large industrial turbine with swept diameters of 300 feet would probably be impractical and economically unfeasible, due to the very large surface areas and associated stresses. We model the bare three-bladed turbine (no shroud) in a 20 m/sec wind stream and 60 rpm (see Fig. 4). Notice cylindrical enclosure or "wind tunnel" surrounding model.

From Equation (1.1), assuming an air density ρ of 1290 g/m$^3$, the general formula for maximum available power is:

$$\text{POWER} = \text{KA } (V_1)^3 \quad (4)$$

Where K = 0.00064 with POWER in kW, A in m$^2$ and $V_1$ in m/s [2].

Accordingly, for our four feet diameter turbine (Area, A = 1.35 m$^2$) and Velocity $V_1$ = 20 m/s, the maximum available power from the wind is 6.9 kW.

Recall from Betz's work that the maximum theoretical value of Cp = 0.59, so that the power output of our turbine = 0.59(6.9 kW) = 4.07 kW if it were a "perfect" machine. From available charts [2] we see that our simple turbine might possibly have a Cp = 0.2 (American multiblade, which approximates our simple turbine, with speed ratio = 0.18). This results in an anticipated power output of 1.38 kW. We shall see if our computer simulation of our bare turbine in a free wind stream (20 m/s) and 60 rpm is close to this result.

We build an imaginary enclosure (computer simulated "wind tunnel" cylinder) around the bare turbine sufficiently far away from the blades so that airflow at the boundaries of the enclosure is undisturbed. We then place an imaginary disk (per Fig. 1) encasing the turbine blades. We will then take the average velocities and pressures at the inlet and at the outlet of the disk (or shroud) itself, not the enclosure, (computed by the simulation) and the energy lost by the wind is the power applied to the turbine blades (neglecting friction) according to the following equation (Bernoulli):

$$P_1/\rho + (V_1)^2/2 = P_2/\rho + (V_2)^2/2 + \text{POWER} \quad (5)$$

Where $P_1$ and $V_1$ are inlet of shroud conditions, $P_2$ and $V_2$ are outlet of shroud conditions, ρ = air density (negligible change in our cases), and POWER = theoretical shaft power gain to turbine.

We will use this analysis throughout our modeling as we add shrouds of different configurations. We change the configuration of the shroud by increasing the included angle THETA (degrees) of the conic section portion of the shroud until a maximum value of power to the turbine is reached and a downward trend begins, except in our special "Stream tube" simulation (Fig. 5).

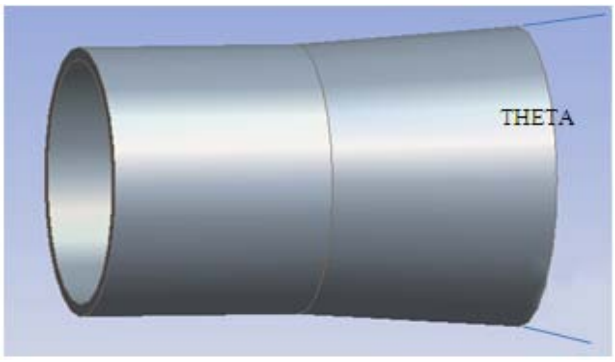



Fig. 5 Shroud showing total included angle THETA

The shrouded turbine model is also encased in an enclosure (computer simulated "wind tunnel") similar to that of the bare turbine with boundaries sufficiently far away from the shroud, ten feet in all three dimensions, so as not to have effects from the turbulence created by the rotating blades (60 rev/min in all cases, except as noted later in paper). The enclosure shall be cylindrical with its axis aligned with that of the turbine. The enclosure has a velocity inlet with boundary conditions set at 20 m/sec, an outlet with boundary conditions of pressure (atmospheric, 101000 Pa), and a far field cylindrical wall with frictionless (free slip) conditions in all cases.

To sum up, we will first model the bare turbine. Then we will model the shroud as a diffuser (velocity inlet on cylindrical section side) at increasing angles of THETA (ten degree increments) and also as a nozzle (velocity inlet on conic section side) at THETA = 20 degrees and 40 degrees. Lastly, we will model the special "stream tube" diffuser and the 300 and 600 rpm simulations. The results will be plotted with the intent of finding those simulations that result in maximum theoretical shaft power to the turbine.

*A Bare Turbine Simulation*

We begin modeling and computer simulations with the bare turbine. We enclose the turbine between two planes (a cylindrical disk). Free stream air is passed over the blades at 20 m/s. Wind velocity (axial component vector only), and pressure averages are computed by the function generator in the ANSYS software for the upstream plane and the downstream plane. Other parameters can also be calculated at any location on the model.

The average velocities at each plane are used to calculate available power in the wind stream at each plane (the difference between the two is the POWER to turbine).

The results for the free turbine above are as follows: average velocity in = 17.48 m/s, average velocity out = 16.60 m/s, average pressure in = 101045 Pa, average pressure out = 100924 Pa, yielding a power of 1.53 kW. This result compares favorably with our theoretical power output of 1.38 kW. We will compare this output to commercially available turbines on a kW/$m^2$ (windswept area) basis in the conclusions section.

In our next case, we will encase the turbine in a cylinder eight feet long (THETA = 0 degrees, no diffuser influence, simply a "pipe" shroud). Our enclosure around the shroud will be as previously described.

The following velocities and areas were calculated in the simulation: average velocity in = 14.24 m/s, average velocity out = 12.38 m/s, inlet and outlet area = 1.35 $m^2$.

These values result in a power output of 0.56 kW, a drastic loss of power from the bare turbine case. Note the velocity at the entrance to the shroud is only 14.24 m/s.

*B Diffuser Shroud Simulations*

In our next case, we increased THETA to ten degrees in the downstream half of our diffuser (see Fig. 5, typical).

The following results were obtained: average velocity inlet = 15.41 m/s, average velocity outlet = 8.6 m/s, inlet area = 1.35 $m^2$, outlet area = 1.73 $m^2$ resulting in maximum theoretical shaft power of 1.43 kW, a marked improvement over the THETA = 0 degree case.

Next, we increased THETA to 20 degrees with the following results: average velocity inlet = 16.21 m/s, average velocity outlet = 5.01 m/s, area inlet = 1.35 $m^2$, area outlet = 2.28 $m^2$ resulting in shaft power = 2.06 kW, a large improvement over the THETA = 10 degree case.

We continued to increase the angle THETA to thirty degrees with the following results (Fig. 6 shows typical simulation): average velocity inlet = 15.92 m/s, average velocity outlet = 3.09 m/s, area inlet = 1.35 $m^2$, area outlet = 3.00 $m^2$ resulting in shaft power = 2.01 kW. We notice the beginning of a downward trend in POWER as a function of THETA.

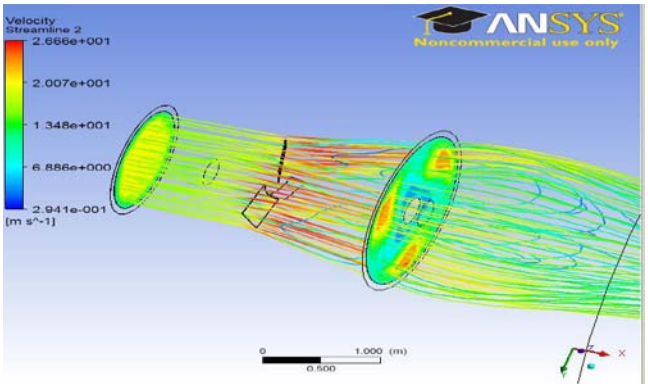



Fig. 6 Typical flow simulation (with shroud, THETA = 30 degrees)

To see if this downward trend continues, we increased THETA to forty degrees. We obtained the following results: average velocity inlet = 15.14 m/s, average velocity outlet = 6.92 m/s, area inlet = 1.35 $m^2$, area outlet = 3.57 $m^2$. These values resulted in a power output of 1.25 kW.

We observe from our simulations a maximum value near THETA = 20 degrees. Further increases in THETA at this point are not necessary. A plot of POWER vs. THETA (diffuser case) will disclose that value of THETA at which theoretical shaft power is a maximum for our diffuser configurations.

*C Nozzle Shroud Simulations*

Now we simulate flow through a nozzle shroud configuration. Our arrangement will be the same as the diffuser shroud (4 ft. of cylinder adjacent to a conic section with varying THETA) but with airflow reversed, the inlet is now on the conic section side.

We remove the turbine, investigate the nozzle shroud only (40 degree) in a 20 m/s wind stream, and note its effect on the wind velocity to see if it also has a significant increase in wind velocity above that of free stream, just as the diffuser.

Results are not encouraging: average velocity inlet = 8.07 m/s, average velocity outlet = 19.32 m/s.

The forty degree nozzle, shroud only, does not increase free wind velocity (in fact, a slight decrease is noted). To verify the inadequacy of the nozzle configuration we examine the twenty degree case.

We get the following results: average velocity inlet = 11.40 m/s, average velocity outlet = 19.66 m/s, another disappointing result. Again, we recognize a decrease in free stream wind velocity. We conclude that the nozzle configuration will be of no use to us to increase wind velocity and thereby turbine shaft power.

We next run the same simulation on a twenty degree diffuser without a turbine inside to see, indeed, if the nozzle results are valid (all parameters being equal), we get the following results: average velocity inlet = 30.81 m/s, average velocity outlet = 18.35 m/s.

We see a large increase in velocity (approximately 50%) over free stream (20m/s), hence, our increase in turbine power shown in earlier simulations.

We conclude that nozzles of our configuration are of no value in increasing power to our wind turbine. We continue our simulations with two more cases ("stream tube" shape configuration and 300 and 600 rpm simulations).

*D "Stream tube" Shape Configuration (Simulation)*

In this simulation, we encase the turbine with a shroud in the configuration of a stream tube (the approximate shape of the streamlines around a propeller or turbine, shown in Fig. 1), with the outlet being 1.75 x inlet diameter in our model.

With outlet/inlet diameters = 1.75, we run the simulation (all parameters equal) and get the following results: average velocity inlet = 20.29 m/s, average velocity outlet = 3.39 m/s, area inlet = 1.35 $m^2$, area outlet = 3.48 $m^2$

These values result in a power output of 4.07 kW. This is a 97% increase over our best case diffuser (THETA = 20 degrees) with a power of 2.06 kW.

*E 300 and 600 RPM Simulations (40 Degree Diffuser Shroud)*

We increase the rpm of the rotor from 60 rpm to 300 rpm and 600 rpm to see if this has a positive effect on power generation. Reference 2 shows that for a given wind speed, there is an associated rpm that maximizes Cp. We select the forty degree diffuser configuration to run these simulations.

We run the 300 rpm simulation with the following results: average velocity inlet = 15.83 m/s, average velocity outlet = 1.06 m/s, area inlet = 1.35 $m^2$, area outlet = 3.58 $m^2$, resulting in a power output of 2.006 kW, an increase of 60% over the 60 rpm simulation.

For the 600 rpm simulation, we get the following results: average velocity inlet = 15.1 m/s, average velocity outlet = 0.29 m/s, area inlet = 1.35 $m^2$, area outlet = 3.58 $m^2$, resulting in a power output of 1.71 kW, an increase of 37% over the 60 rpm simulation.

The above results show that there is an optimum rpm, at which the power output can be maximized. Therefore the results are consistent with Reference 2.

## III. PLOTS AND RESULTS

From our simulations, we now summarize our findings. We determine that indeed power can be augmented to a bare turbine by the addition of a diffuser shroud assembly. We note that velocity can be increased from 20 m/s (free stream) to 30.81 m/s by means of the 20 degree diffuser shroud only (no turbine inside) in our simulation, a 54% increase.

Fig. 7 shows power output as a function of the diffuser angle "THETA". We see from this graph that POWER at THETA = 0 degrees (cylinder) is relatively small but increases steadily until a maximum of 2.10 kW reaches at THETA = 25 degrees, an increase in POWER of 52% over the theoretical power output of 1.38 kW (assuming a Cp of 0.2). Also we note an increase in POWER of 37% over the power calculated from our simulation of the bare turbine (1.53 kW).

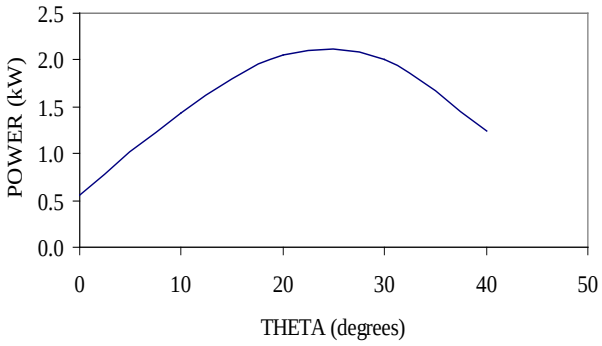



Fig. 7 Power output of diffuser augmented wind turbine as a function of THETA

As we saw, the nozzle shroud simulations showed negative results. The twenty degree and forty degree shrouds (with no turbine inside) actually decreased the free wind velocity from 20 m/s to 19 m/s in contrast with those of the twenty degree diffuser, where we saw an increase from 20 m/s to 30.81 m/s. Consequently, we determine that the nozzle shroud configuration has no ability to augment turbine POWER.

Our "stream tube" shroud seems to be the most promising. We note an increase in POWER of 97% above that of our best case diffuser (THETA = 25 degrees), also note that this is a diffuser type shroud.

Lastly, we investigated turbine rotor rpm and its effect on coefficient of performance (Cp) for our particular turbine. As stated previously, all of our simulations were done at 60 rpm. We increased rpm to 300 and 600 and plotted the results for the forty degree diffuser case (Fig. 8).

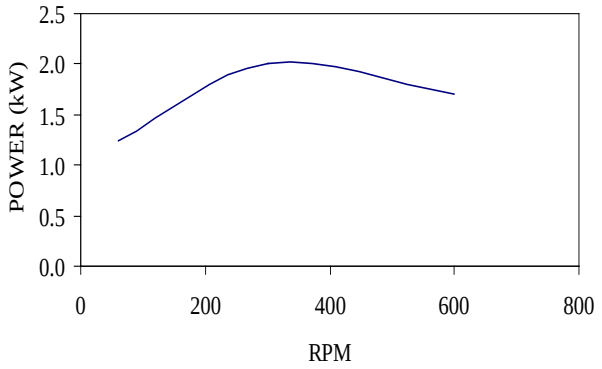



Fig. 8 Power output of diffuser augmented wind turbine as a function of rpm

For our particular turbine, maximum efficiency occurs at 400 rpm with POWER output of 2.05 kW (at the given wind velocity = 20 m/s).

To sum up, from the plots, we get maximum performance (Cp) when we enclose our bare turbine in a diffuser shroud with THETA = 25 degrees and a rotor angular velocity of 400 rpm (42 rad/s). However, much greater efficiency may be expected when coupling our bare turbine with the special "stream tube" diffuser shroud with turbine rotation at 400 rpm.

## IV. CONCLUSIONS

As we stated in the introduction, the diffuser shroud concept is probably most suited to small and medium sized wind turbines (probably less than 25 ft. diameter). Any size larger than this would probably require substantial reinforcing of the entire structure due to wind load (and the associated initial capital cost).

One advantage of the diffuser is that it should align itself into the wind, thus eliminating the need for a rudder downstream of the blades. Another advantage is that it should be maintenance free. It is simply a passive device that allows increased production of electricity over the life of the turbine. It could even outlast the turbine and be recycled on the next turbine. Comparing our turbines with the twenty-five degree diffuser and the "Stream tube" diffuser with two comparable commercially available turbines we have the following results:

1) "Air dolphin GTO" [4], Rotor diameter: 6 ft., POWER at 20 m/s wind velocity: 4 kW, SWEPT area: 2.66 $m^2$, POWER/SWEPT area = 1.5 $kW/m^2$.
2) "Sky stream 3.7" [5], Rotor diameter: 12 ft., POWER at 20 m/s wind velocity: 2.4 kW, SWEPT area: 10.86 $m^2$, POWER/SWEPT area = 0.22 $kW/m^2$.
3) Our turbine with 25 deg. Diffuser shroud, Rotor diameter: 4 ft., POWER at 20 m/s wind velocity: 2.1 kW, SWEPT area: 1.35 $m^2$, POWER/SWEPT area = 1.55 $kW/m^2$.
4) Our turbine with "Stream tube" shroud at 60 rpm, Rotor diameter: 4 feet, POWER at 20 m/s wind velocity: 4.07 kW, SWEPT area: 1.35 $m^2$, POWER/SWEPT area = 3.01 $kW/m^2$.

We see that our simply designed turbine with diffusers exceeds both commercial turbines in power output/$m^2$ (by a large margin in the "Sky stream" turbine). Further increases in power may be expected from our turbine with the addition of the "Stream tube" shroud with turbine angular velocity of 400 rpm (we did not run the simulation in this particular case).

## V. FUTURE WORK

Further research in this realm of wind turbine design could be as follows:

1) making the shroud more streamlined (aerodynamic) than the simple shapes we have included in this paper;
2) combining the diffuser presented here with a much improved turbine design, possibly one with many more blades and/or blades of an improved aerodynamic design;
3) considering adding additional stages (rotors) coaxially to gather more kinetic energy from wind;
4) doing a feasibility study (economics) of placing diffuser shrouds on medium to large turbines (25-150 ft. diameters);
5) placing shrouds around other turbine configurations (for example a vertical axis wind turbine VAWT) to improve the Cp (coefficient of performance);
6) investigating various materials to make the shroud and their pros and cons (small shrouds might need one material and large ones, another);
7) trying other ways to mount the shroud on the turbine body;
8) lastly, investigating further the "stream tube" shaped shroud simulated earlier. This shroud has showed the greatest increase of theoretical turbine shaft power of any simulation.

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